ENHANCING CONTAMINANT REMOVAL IN STORMWATER DETENTION BASINS BY COAGULATION

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ABSTRACT

The Washington State Department of Transportation designs, operates, and maintains stormwater detention basins for flood control. Historically, detention basin design was based primarily on hydraulic characteristics such as storage capacity. Initiatives by the Washington State Department of Ecology have prioritized the consideration of stormwater quality as well as quantity for stormwater treatment. Consequently, current operation and future design should consider water quality in addition to flood control.

A scale model of a typical basin was constructed to investigate contaminant removal capabilities of existing detention basins. Particular attention was given to the enhanced removal of smaller sediment size fractions and heavy metal contaminants adsorbed to those fractions. Using typical contaminants and concentrations, a simulated highway stormwater runoff was formulated and applied in scale model detention basin testing over a range of flow rates. Four coagulants were evaluated for their ability to enhance removal of sediment and metals. Each coagulant was initially evaluated in laboratory scale batch experiments with continued model tests on selected coagulants.

In the model detention basin, coagulant addition resulted in significant increases in metal removal over the range of stormwater flow rates studied. The greatest improvement was observed at the higher flow rates. Enhanced metals removal resulted from increased removal of small particles and their adsorbed metals. Further improvement in contaminant removal was observed following the addition of an influent baffle. This baffle resulted in an increase in hydraulic detention time by reducing short circuiting with an associated improvement in contaminant removal.

INTRODUCTION

Contaminants in highway runoff can have deleterious impacts on receiving waters. Portele, *et al*. report adverse effects of soluble fractions of contaminants on zooplankton and algae, while suspended solids cause high mortality of rainbow trout fry (*1*). Another study reports elevated lead concentrations in barn swallows nesting adjacent to highways (*2*). Washington State Department of

Ecology has declared limiting highway borne contaminants a high priority (*3*). In response to known and suspected impacts of highway runoff on receiving waters, the Washington State Department of Transportation (WSDOT) has been involved in stormwater quality monitoring and control since the 1970's.

Studies aimed at quantifying highway runoff characteristics and determining best management practices have found that grassy swales, wetlands, retention/infiltration basins, and dual purpose detention basins could be effectively used for removing a variety of stormwater contaminants under certain system conditions and receiving water constraints (*4—7*). Generally, grassy swales and wetlands provided the highest degree of treatment. The most common management practice, however, is dual purpose detention basins, initially constructed as flood control devices. These basins were designed to store a portion of a storm event and then release that water over an extended time period. Although flood control was the primary application, most also exhibited an ability to remove particulate matter, as evidenced by the need to periodically remove accumulated sediments from the basins. In most cases however, their sediment removal efficiency has not been quantified, and as a result, rational design information is unavailable.

Cole and Yonge (*8*), through scale model testing, determined that discrete particle settling theory can be used to estimate sediment removal in stormwater detention basins. Sediment removal efficiencies ranged from 65 percent to 80 percent as a function of flow and model basin inlet/outlet configurations. Theoretical model predictions were within seven percent of measured sediment removal values. Preliminary tests indicated that metal removal ranged from 28 percent to 40 percent, significantly less than observed sediment removal values. It was determined that this was a direct result of the inverse relationship between metal partitioning and sediment size (*8—12*). As a result of their small size and lower settling velocities, the smaller size fraction are only partially removed in a detention basin. Similar contaminant removal results were observed which show that the failure to remove small particulate matter would prevent achievement of target discharge concentrations for certain contaminants (*13*). Based on these results, it is apparent that enhanced metals removal could be accomplished by increasing the removal of the smaller sediment size fraction.

An increase in capture efficiency of the smaller sediment size fraction could be realized by increasing basin surface area resulting in a decrease in surface overflow rate (SOR) (*14*). This option would likely not be cost effective or there may be physical constraints, such as space availability, that prevent implementation if the desire is to use existing basins for contaminant retention. One method of increasing removal of sediment and associated contaminants without physical basin modification is through the application of chemical coagulants to the stormwater influent. Chemical coagulation is a common practice in water and wastewater treatment applications and would be effective in some detention basin systems. Enhanced sediment removal would result from an increase in particle size through particle charge neutralization and particle—particle bridging (referred to as floc formation) to form aggregates of the smaller particles (floc). The larger aggregates have higher terminal settling velocities, resulting in increased particle removal at a given SOR. This paper presents the results of a study developed to determine the influence of coagulant addition on stormwater contaminant removal in a scale model detention basin.

EXPERIMENTAL METHODS

Development of Simulated Stormwater

The data in Table 1 summarizes the constituents and their concentrations used in the simulated stormwater (SSW). These concentrations were selected based on literature values and are within a range of concentrations as defined by national average values (*15*).

The sediment used in the SSW was obtained from Wallowa lake in eastern Oregon. The sediment at this site was selected for its minimal indigenous heavy metal concentrations, since there is no road access upstream of the lake, and thus, little likelihood of contamination by automobile pollutants. The sediment was transported to the laboratory and stockpiled on a tarp at a depth of approximately 0.15 m (0.5 ft) and air dried at ambient temperatures (approximately 20 °C) for several weeks. The soil was undisturbed during drying to minimize unintentional stratification. The dried sediment was shaken on a US Standard #28 sieve (0.625 mm mesh size) using a Soiltest hammer—type shaker for 15 minutes to remove larger size fractions and unwanted debris. The fraction passing through the #28 sieve was then ground on a Cincinnati muller—type grinder for 30 minutes to reduce the sediment to elementary particles. After grinding, the soil was shaken in a sieve stack for 30 minutes and all sediment that had passed the #200 sieve (0.075 mm) was used for preparing the SSW. Hydrometer analysis (ASTM D—422) was then performed to define the particle size distribution of the sediments.

Bench Scale Evaluation

Four coagulants, $Al_2(SO_4)_3 \cdot 18H_2O$, $FeCl_3 \cdot 6H_2O$, and two cationic inorganic coagulants (SWT 848 and SWT 976, Southern Water Treatment Co., Greenville, SC) were evaluated in bench scale, jar test experiments. Evaluation included qualitative (supernatant clarity and floc settleability) and quantitative assessment (metals removal, sediment removal, and rate of floc formation). Two jar test procedures were performed. The first procedure followed ASTM specifications (e.g., 1 minute rapid mix, 20 minute slow mix, 30 minute settling period) while the second procedure included modifications designed to more closely simulate initial mixing and contact times in the model detention basin (0.5 minute rapid mix, no slow mix, 4—11 minute settling period). Variable settling periods afforded a means of evaluating coagulant effectiveness in terms of the rate of floc formation.

Scale Model Detention Basin

Model experimentation was performed on a 1:15 scale model of a stormwater detention basin located near Interstate 5 in Olympia, Washington. This basin was selected because its geometric similarity is representative of numerous basins in the area. Model SSW flow rates were determined by maintaining equivalent SOR's between the field basin and the scale model (*8*).

Model Detention Basin Experiments

Figure 1 is a schematic representation of the model detention basin experimental apparatus. A concentrated (approximately 32 times the basin influent concentration) homogeneous contaminant slurry was maintained in a 115 L Nalgene tank. Use of a concentrated slurry was necessary because of the logistical difficulty required to prepare and maintain a homogenous solution of SSW in a 3800 L tank. The slurry solution was blended with tap water from a feed tank in a completely—mixed blend tank. This served to dilute the slurry to target contaminant concentration values (Table 1). In addition, coagulant was metered into the blend tank for those experiments involving coagulant addition. All flows were controlled by variable speed peristaltic pumps. Flow rate was calibrated prior to each experiment and measured at its completion. Triplicate runs were performed at one flow rate and a constant coagulant dosage to define experimental error.

Scale model experiments were performed at four flow rates, defined in Table 2. Once flows of the slurry, coagulant, and dilution water streams were adjusted to desired values, four basin hydraulic residence times were allowed to pass prior to sample collection to allow effluent solution characteristics (e.g., solution constituent concentrations) to achieve steady—state conditions. Two, 250 mL samples were taken at 20 second intervals at both the influent and effluent. Each sample pair was composited and placed in a 600 mL baffled glass beaker with a Teflon magnetic stir bar and mixed on a magnetic stirrer. Two duplicate sets of 50 mL samples were removed from the composite and analyzed for soluble and total (soluble + adsorbed) metals. A metals digestion procedure using nitric acid was optimized for the sediment used in this study (*8*). Metals quantification was afforded by atomic absorption spectroscopy (AAS) using a Varian SpectrAA—300 atomic absorption spectrometer, the details of which can be found in Cole and Yonge (*8*). Dry weight suspended solids concentrations were determined by measuring the weight of solids retained on the filter used in the soluble metal sample preparation.

Tracer Study

Conservative tracer experiments were performed to investigate the hydraulic response of the basin to the installation of an inlet baffle. The baffle was placed perpendicular to the direction of flow, 46 cm (18 in) from the point where the inlet flow stream entered the basin pool. A pulse input of NaCl was injected in the influent flow stream of the basin and effluent specific conductivity was monitored as a function of time to define the tracer response profile. The baffle conformed to the bottom profile of the basin and was constructed from 0.64 cm (0.25 in) thick Plexiglas sheet. Holes (1 cm diameter, uniformly spaced at 4 cm on center) were drilled through the baffle to obtain a more evenly distributed velocity profile over the basin cross—section.

Fines Partitioning

Characterization of metal sorption as a function of soil particle size was achieved in a bench—scale settling column experiment. The sediment was equilibrated with the metals at slurry tank concentrations for 24 hours. Two liter aliquots of the equilibrated soil slurry was placed in five, 2 L graduated cylinders. Samples were collected from a fixed location (15 cm from the top of the cylinder) at predetermined time intervals. These samples were analyzed for total metal, soluble metal, and suspended solids concentrations. Adsorbed metal concentrations were determined by difference. Each sample was also characterized with respect to mean particle size using a particle size distribution analyzer (Horiba CAPA—700).

RESULTS AND DISCUSSION

Jar Test

The four coagulants investigated exhibited to varying degrees, at least some ability to remove suspended solids under standard ASTM jar test protocol. However, the modified jar test procedure indicated that $Al_2(SO_4)_3 \cdot 18H_2O$ and SWT 976 were ineffective at destabilizing the sediment suspension and initiating floc formation in the relatively short rapid—mixing period. As a result, these two coagulants were not used in the model basin experiments. Conversely, $FeCl_3 \cdot 6H_2O$ and SWT 848 performed well, exhibiting rapid floc formation and good solids settling characteristics.

The optimum dosage for $FeCl_3 \cdot 6H_2O$, based on sediment and metals removal, was 15 mg/l as Fe. It was noted that the optimum fell in a narrow range; concentrations 15 percent less or greater resulted in a significant deterioration in contaminant removal performance. Suspended solids and metal removal using SWT 848 was found to be much less sensitive to dosage once a minimum threshold value of 50 mL/L was achieved, exhibiting a wide window of operation. This characteristic is important when considering highway stormwater detention system design. The high number of basins to maintain and remote location requires a simple, low maintenance method of coagulant application. Obviously, a coagulant that performs effectively over a broad concentration range would be preferred in such systems.

Metals Partitioning

The data in Figure 2 describes the influence of sediment particle size on sorption capacity. Sorption of zinc exhibited the least sensitivity to particle size of the four metals, with a solid phase capacity that was 4.7 times greater on 4mm particles than 17 mm particles. Lead, representative of metals having stronger sorption characteristics, exhibits a 4 mm particle sorption capacity that was approximately 6 times greater than that for 17 mm particles. The relationship presented in Figure 1 indicates that increases in detention basin contaminant removal can be achieved by increasing removal of the smallest particles.

Model Basin Performance

Several preliminary basin experiments were performed to define optimum coagulant dose with respect to metal removal for $FeCl_3 \cdot 6H_2O$ and SWT 848. These tests indicated that $FeCl_3 \cdot 6H_2O$ was sensitive to dose, requiring dose optimization for each of the four test flow rates. Conversely, SWT 848 did not exhibit dose sensitivity over the range of flow rates studied, confirming the results of the jar test experiments.

The metals removal data in Figure 3a—d show the influence of coagulant addition upon metal removal over the range of SOR's studied. Two general trends are apparent: (i) metal removal is inversely proportional to SOR and (ii) coagulant addition results in a statistically significant (at a 95% confidence level) improvement in contaminant removal. Additionally, it can be seen that SWT 848 outperformed $FeCl_3 \cdot 6H_2O$.

Sediment removal data (Figure 4) also exhibits the inverse relationship between flow rate and removal. However, coagulant addition appears to *decrease* solids removal. This anomaly is a result of the influence of the coagulant on the suspended solids analysis procedure. Some of the coagulant was retained on the filter from the suspended solids sample, even after thorough rinsing (by filtering deionized water) and drying at 104 °C; thus, measured solids concentrations incorporate the weight of both the sediment and coagulant retained on the filter. Since floc formation is time dependent, more aggregated coagulant was measured in the effluent samples than in the influent samples, giving the appearance of decreasing solids removal, when sediment removal was actually enhanced.

Further enhancement of contaminant removal was evaluated by modifying basin hydraulics by the insertion of a baffle. Experiments were performed during coagulant addition (SWT 848) to assess baffle influence on contaminant removal. The data in Figure 5a—d shows significant improvement in removal at the two highest SOR's (242 mm/sec and 302 mm/sec) for all metals. This is a result of an improvement in basin hydraulics that afforded a reduction in basin short—circuiting and an increase in solids and adsorbed metal capture.

Improved basin hydraulics, following baffle placement, can be observed in the tracer response profiles plotted in Figure 6. It can be seen that the maximum tracer concentration was recorded at 0.7 min. for the unbaffled condition. This response profile indicates that significant short—circuiting is occurring when a comparison is made to the theoretical basin detention time of 5.5 min. Baffle installation results in a shift of the maximum tracer concentration to 2.2 min., indicating a significant reduction in short—circuiting. Therefore, the observed improvement in contaminant removal at the higher SOR's using a baffled system is probably the result of a reduction in short—circuiting. This results in a more uniform flow distribution through the system, improving floc formation and sediment removal efficiency.

CONCLUSIONS

Results of scale model detention basin testing indicate that significant improvement in contaminant removal can be obtained by the addition of chemical coagulants. This improvement was a result of enhanced removal of smaller sediment size fraction and the associated metals. For example, over the range of flows studied, sediment removal (without coagulant addition) varied from approximately 60% to 75% while lead removal varied from 15% to 35%. Coagulant addition resulted in lead removals of 38% to 77%.

Ferric Chloride and SWT 848 resulted in the best overall performance while alum and SWT 976 were found to be ineffective under the conditions studied. It was concluded that coagulant effectiveness with regard to contaminant removal was primarily dependent upon rate of floc formation. This attribute would be important under field application conditions where the coagulant would be added in the influent flow stream (e.g., a culvert or ditch). Under this condition, the coagulant would have to induce coagulation in a short time period. In addition, to afford unattended operation, the coagulant should be effective over a wide concentration and pH range.

Preliminary coagulant screening should be carried out with stormwater samples collected in the field that cover a range of anticipated water quality conditions. A modified jar test procedure was developed and should be used during the screening procedure as this will afford results that are representative of anticipated field conditions. The procedure was developed to simulate the conditions in the scale model and consisted of:

- 0.5 minute rapid mix,
- 4—11 minute settling period with no mixing.

The settling period was selected to simulate anticipated basin conditions for each flow rate studied. This afforded a means of evaluating coagulant effectiveness in terms floc formation potential for each basin hydraulic detention.

This procedure should be modified, as necessary, to mimic the conditions for a particular detention basin system. For example, if there is a one minute detention time from the point of coagulant addition to the detention basin and a 10 minute average hydraulic detention time in the basin then the jar test conditions should be rapid mix for one minute followed by ten minute settling period. Following the settling period, supernatant would be collected for testing. This testing would be most efficiently carried out by measuring turbidity during the initial screening procedure. If more detailed information is desired, samples could be analyzed for specific contaminants of interest.

The importance of basin hydraulics in contaminant removal efficiency was made evident by the placement of an influent baffle that more evenly distributed the flow across the cross section of the basin, reducing hydraulic short circuiting and increasing contaminant removal. If flow hydraulics are not obvious from a detention basin field survey, a conservative tracer experiment should be performed to estimate the degree of short circuiting. If it is determined that basin hydraulics should be improved, a field scale influent flow device would be relatively inexpensive to fabricate and install.

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LIST OF TABLES AND FIGURE TITLES

TABLE 1 Simulated Stormwater Constituents and Their Target Concentrations

Constituent	Concentration ($mg\ L^{-1}$)
Suspended Solids	500
Lead	1.8
Cadmium	0.06
Copper	0.18
Zinc	1.3

TABLE 2 Model Basin Influent Flow Rates and Corresponding Surface Overflow Rates.

Influent Flow Rate ($L\ min^{-1}$)	Surface Overflow Rate ($\mu m\ sec^{-1}$)
45.4	302
34.1	242
26.5	205
18.9	148

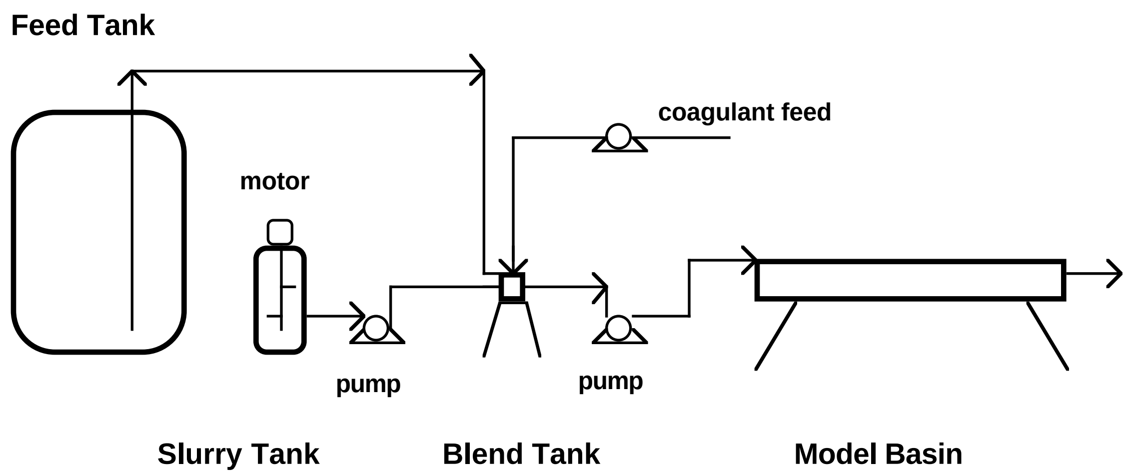


FIGURE 1. Schematic Representation of Model Basin Experimental Apparatus.

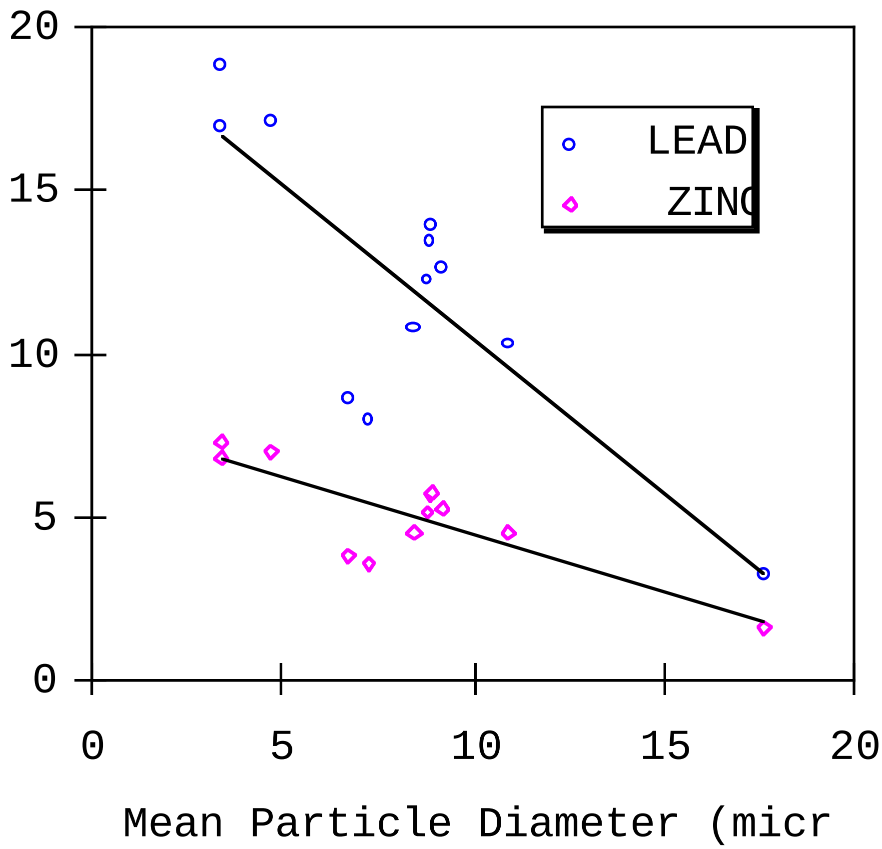
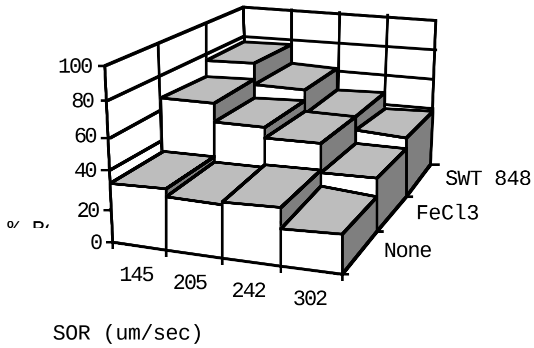
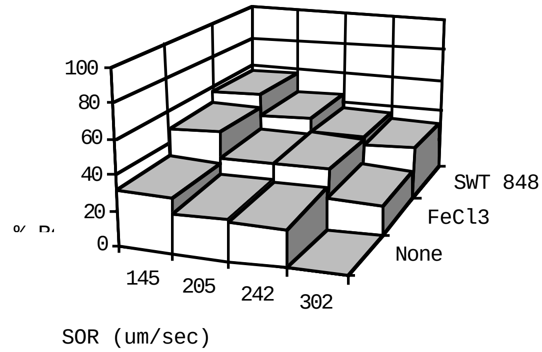


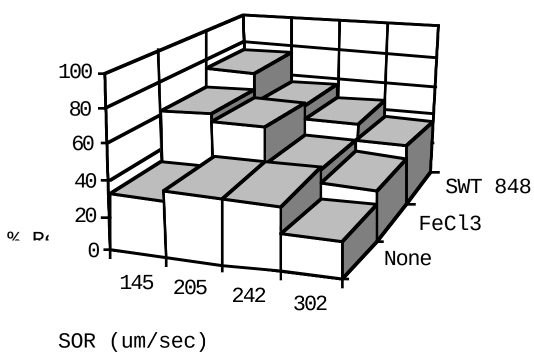
FIGURE 2. Influence of sediment particle size on equilibrium adsorption capacity for Pb and Zn.



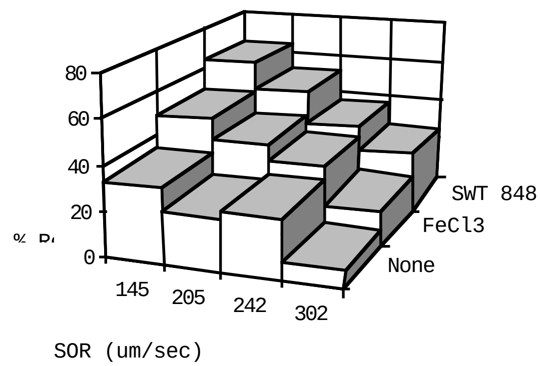
(a) Pb



(b) Cd



(c) Cu



(d) Zn

FIGURE 3. Effect of Flow and Coagulant Addition on Metals Removal. (a) Lead. (b) Cadmium. (c) Copper. (d) Zinc.

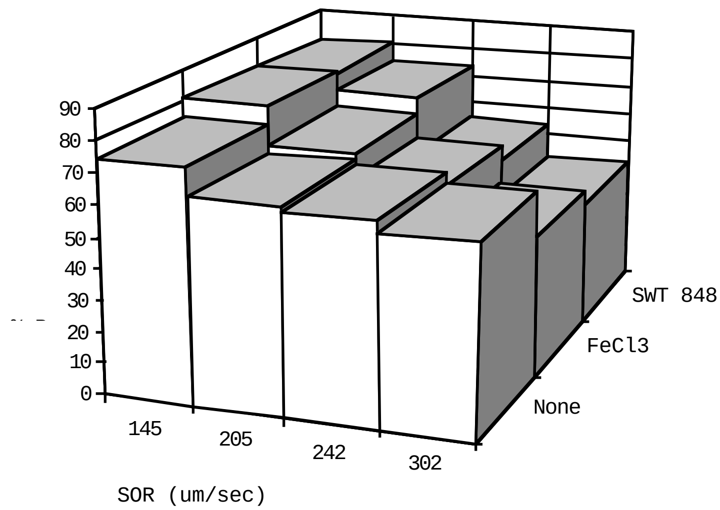
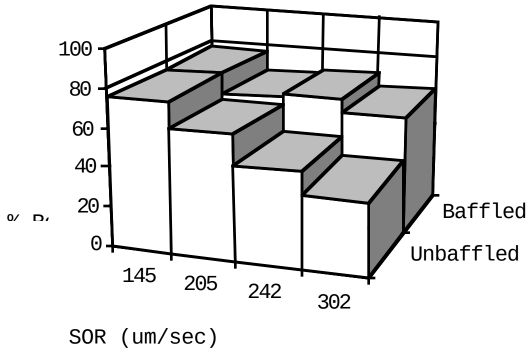
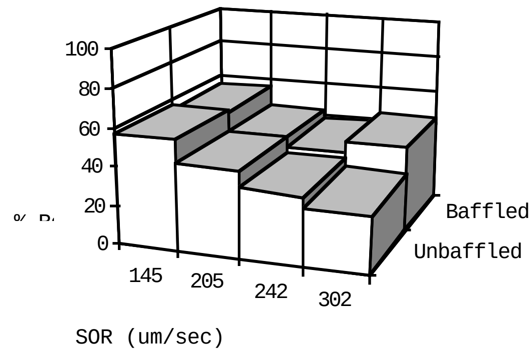


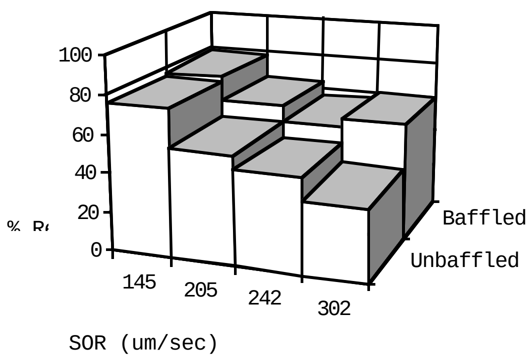
FIGURE 4. Effect of Flow and Coagulant Addition on Suspended Solids Removal.



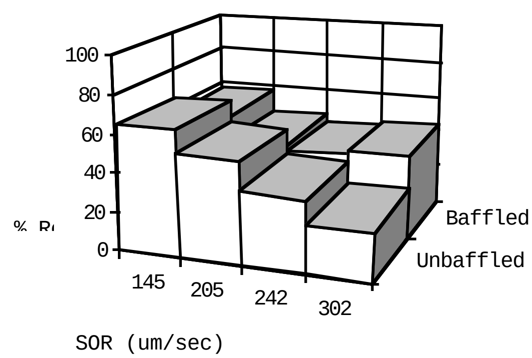
(a) Pb



(b) Cd



(c) Cu



(d) Zn

FIGURE 5. Influence of a Baffle on Metals Removal During the Coagulation by SWT 848. (a) Lead. (b) Cadmium. (c) Copper. (d) Zinc.

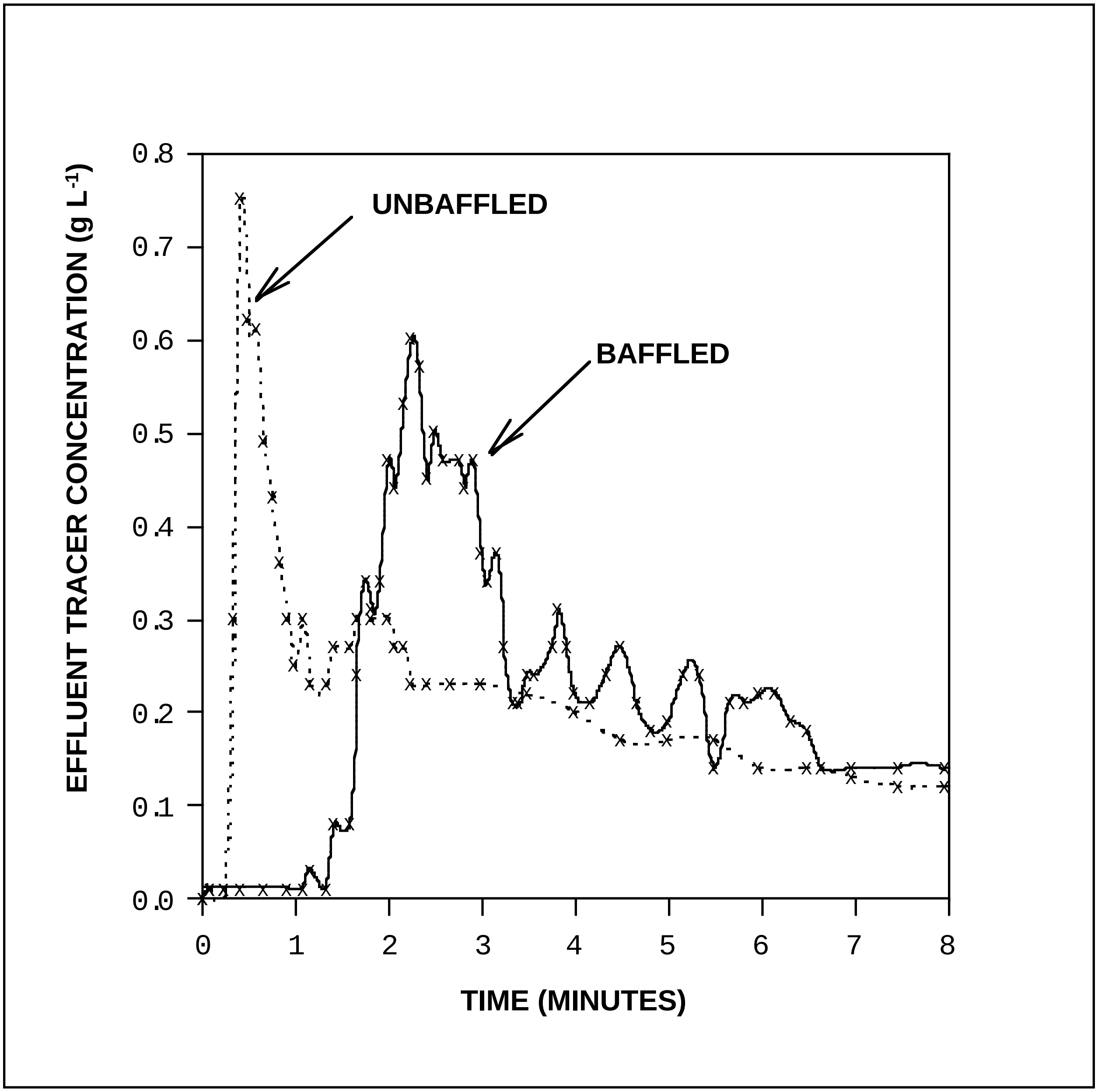


FIGURE 6. Impulse input conservative tracer response profile (SOR = 302 μm/sec).